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A study on piezoelectric actuators and sensors for vibration control of flexible space structures

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NAVAL POSTGRADUATE SCHOOL
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THESIS

A STUDY ON PIEZOELECTRIC
ACTUATORS AND SENSORS
FOR VIBRATION CONTROL
OF FLEXIBLE SPACE STRUCTURES

by

Franklin D. Hixenbaugh

September, 1993

Thesis Advisor: Brij N. Agrawal

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This thesis details the procedure for applying piezoelectric ceramic material to the Naval Postgraduate School's Flexible Spacecraft Simulator (FSS) for the purpose of active damping control. A step by step procedure to properly mount and test piezoelectric ceramic actuators and sensors is developed followed by performance demonstration by two control laws: Positive Position Feedback (PPF), and Proportional Derivative (PD). A digital controller for PD control is also developed.

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A STUDY ON PIEZOELECTRIC ACTUATORS AND SENSORS FOR VIBRATION CONTROL OF FLEXIBLE SPACE STRUCTURES

by

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ABSTRACT

This thesis details the procedure for applying piezoelectric ceramic material to the Naval Postgraduate School's Flexible Spacecraft Simulator (FSS) for the purpose of active damping control. A step by step procedure to properly mount and test piezoelectric ceramic actuators and sensors is developed followed by performance demonstration by two control laws: Positive Position Feedback (PPF), and Proportional-Derivative (PD). A digital controller for PD control is also developed.

TABLE OF CONTENTS

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I. INTRODUCTION

A. BACKGROUND

The high cost to put an object into orbit has constrained many engineers to design spacecraft to be as light as possible. These low mass constraints have resulted in spacecraft structures which are flexible with low frequency fundamental vibrational modes. The Control-Structures Interaction (CSI) field has emerged in order to meet the challenges of controlling flexible structures. [Ref. 1]

The Flexible Spacecraft Simulator (FSS) at the Naval Postgraduate School implements piezoelectric ceramic elements as sensors and actuators for active damping of flexible arms. A significant amount of damping has been achieved with one set of near co-located sensors and actuators mounted on the first arm of the FSS.

B. SCOPE OF THESIS

This thesis will establish a procedure to successfully mount piezoelectric ceramic elements to a flexible structure. Two additional sets of sensors and actuators will be added to the second arm of the FSS. The sensors and actuators will be hard-wired and tested for proper operation after mounting. An additional air bearing table will be constructed to allow testing of actuators and sensors when the granite table is in

use. A Proportional Derivative (PD) control law will be implemented using LABVIEW 2®, a graphical interface for control system design developed by National Instruments, on the Macintosh computer. The controller will be a digital control type, based upon the two sets of sensors and actuators mounted on the second arm of the FSS.

The majority of the thesis will be hardware orientated. Much of the basic theories on operation of piezoelectric material has already been published in previous studies, (Ref. 1), and will not be repeated in this thesis.

II. APPLICATION OF PIEZOELECTRIC CERAMICS TO A STRUCTURE

A. DETERMINATION OF LOCATION

One of the best locations for applying surface mounted piezoelectric ceramics to a flexible structure, is in an area of highest strain energy [Ref. 2]. At this point one can expect high sensitivity of sensors and high efficiency of actuators. This issue of locating sensors and actuators on large space structures has been one of extensive research areas. Beams with cantilevered ends have highest strain energy near the clamped end of the beam. Both ends of the second arm of the FSS have been chosen for the locations of the piezoelectric ceramic actuators and sensors, due to the high strain energy present and high element strain energy percentage for important modes.

B. SURFACE PREPARATION

1. Inspecting Surface

The surface must be clean, smooth, and free of any nicks or scratches to ensure proper adhesion of the piezoelectric ceramics. If it is necessary to mount a piezoelectric ceramic actuator or sensor over an existing hole, the hole must be chamfered to lower the stress concentration factor to prevent possible depoling of the piezoelectric ceramic.

2. Sanding

Waterproof sandpaper is used with water to remove any paint or scratches from the mounting surface. Initial sanding can be accomplished with 240 or 400 grit sandpaper. Final sanding with 600 grit sandpaper will properly finish the surface prior to mounting the piezoelectric ceramics.

3. Cleaning

Clean the surface with ethanol alcohol and remove any grit and/or residue. Isopropyl alcohol is an acceptable substitute for ethanol. Allow the surface to air dry and avoid touching the clean surface with bare fingers.

C. CUTTING THE PIEZOELECTRIC CERAMICS

1. Sizing

Determine the dimensions necessary for the actuators and sensors to be mounted. Actuators are usually made larger so that more strain can be applied to the flexible structure for active damping. Layout and cut all actuators first so that if errors are made the pieces can be re-cut to make sensors. This will minimize the amount of wasted piezoelectric ceramic material.

2. Poling Labels

During manufacture, piezoelectric ceramics are heated to a temperature above their curie point while an electric field is applied. This causes the crystalline structure to elongate in a direction parallel to the electric field or

poling axis. The poling axis is labeled with a small dot on the face of the piezoelectric ceramic in which the poling axis comes out of. Labelling the poling axis is very important in order to predict the response of the piezoelectric ceramic material in the actuator and sensor modes. When a voltage is applied, which induces an electric field parallel to the poling axis direction, the material will elongate in this direction and foreshorten in the perpendicular directions. When a piezoelectric ceramic material is subjected to a strain, which elongates the material in the poling direction, a voltage will be produced with the same polarity as the original poling voltage [Ref. 3].

It is extremely important that all pieces of piezoelectric ceramic material are marked to indicate poling direction prior to cutting (Fig.1). Without proper marking it is impossible to visually determine poling direction.

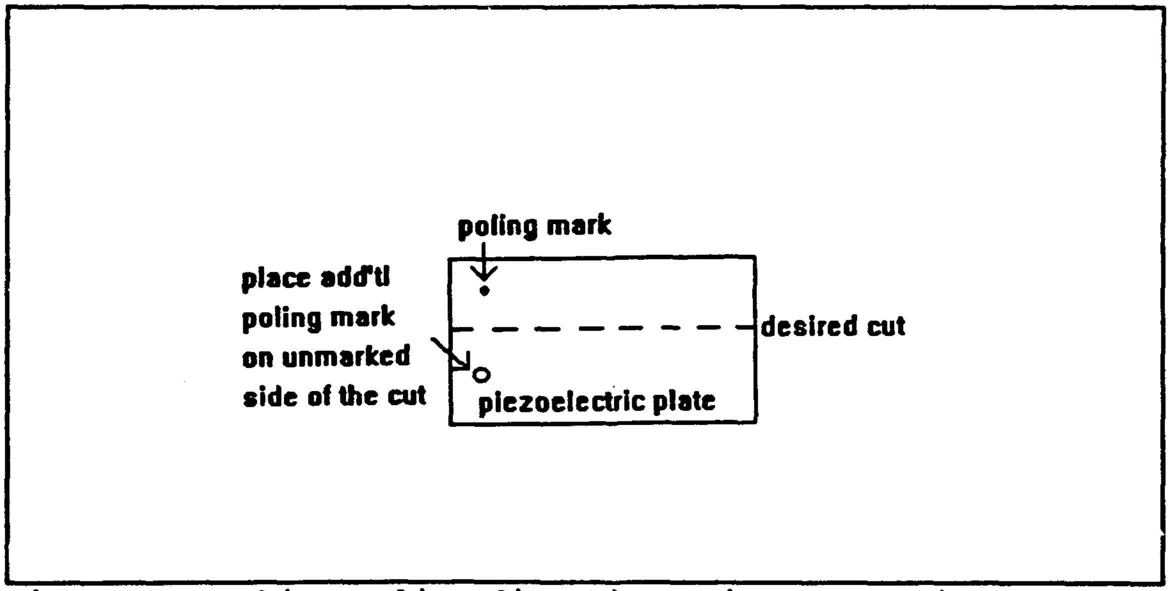

Figure 1 Marking poling direction prior to cutting

3. Scoring Piezoelectric Ceramics

Using a straight edge (a six inch steel rule works well) and an Exacto® or utility knife score one side of the piezoelectric ceramic at the desired cutting location. Several passes with the knife blade may be necessary to properly score the piezoelectric ceramic to obtain a clean break. Do not cut completely through the piezoelectric ceramic. This will cause the brittle material to break with a jagged edge.

4. Securing The Piezoelectric Ceramic

Sandwich the piezoelectric ceramic between two small pieces of safety glass aligning the scored line with the glass edges (Fig. 2). Apply pressure to the glass plates to securely hold the piezoelectric ceramic.

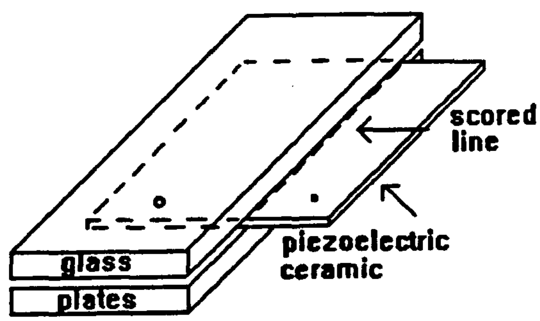

Figure 2 Breaking the piezoelectric ceramic along line

5. Making The Cut

Lay a straight edge flat on the protruding piece of the piezoelectric ceramic that is to be removed. By applying even pressure on the straight edge, while holding the glass plates together, the piezoelectric ceramic will break cleanly along the scored line. Inspect the newly cut edge and remove any nickel plating that could possibly short out the piezoelectric ceramic by bridging across the edge.

D. HARD-WIRING PIEZOELECTRIC CERAMICS

1. Making Conductors

Scissors can be used to cut one eighth inch by two inch conductors out of thin, (two - three mil thickness), copper shim stock. Flatten out the copper conductors after cutting, by placing flat on a hard surface, then drawing the edge of a straight edge over the strip. To minimize the curling of the copper conductor, alternate sides when flattening (Fig. 3).

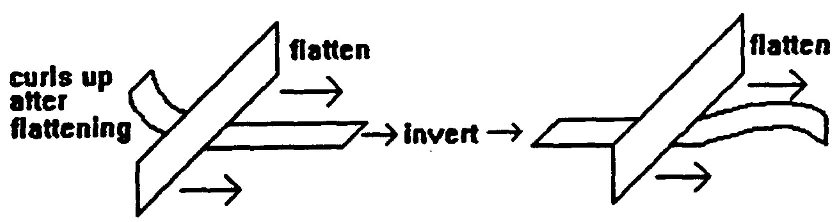

Figure 3 Flattening copper conductors

2. Piezoelectric Ceramic Orientation

The piezoelectric ceramics must be properly oriented with respect to their poling directions so that the voltage induced or applied has the same polarity for all surfaces that are in electrical contact. As a general rule, if piezoelectric ceramics will be mounted on both sides of a beam, the poling direction must be reversed on either side (Fig. 4). Also, if piezoelectric ceramics are going to be in a stacked arrangement, similar pole directions must be in contact with each other (Fig. 5).

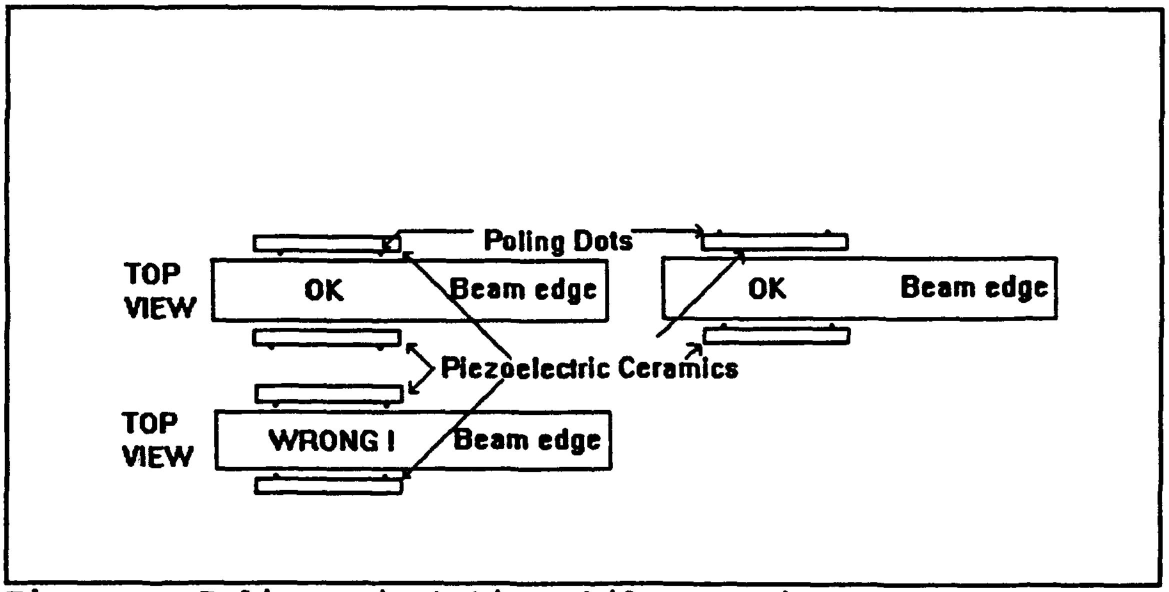

Figure 4 Poling orientation while mounting

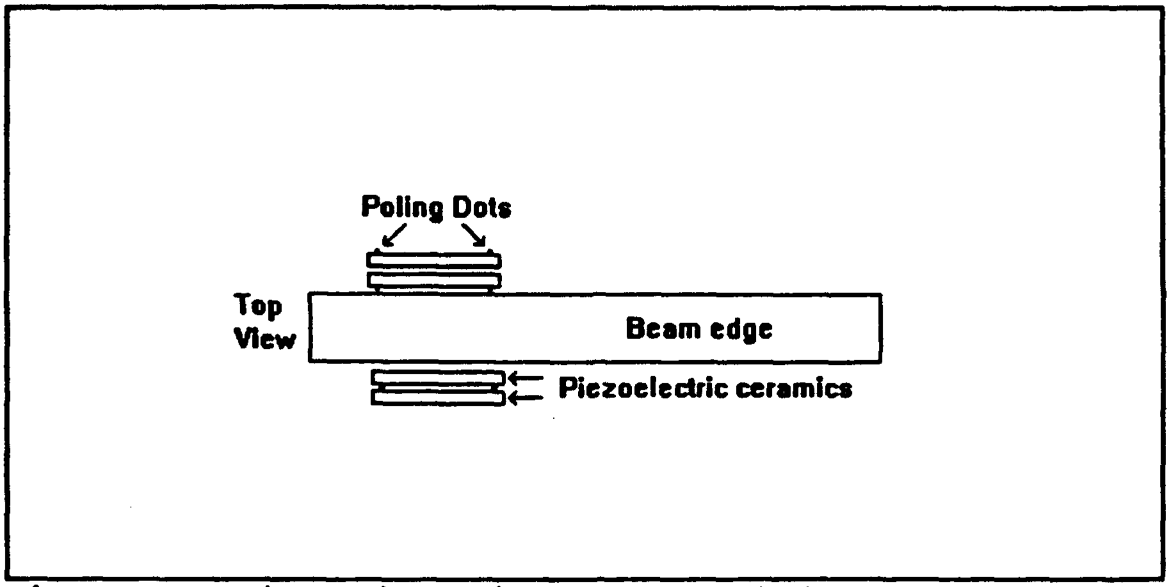

Figure 5 Poling orientation for a stacked arrangement

3. Soldering Conductors to Pièzoelectric Ceramics

One copper conductor strip will be silver soldered to the center of the piezoelectric ceramic on the side which will be attached to the beam (Fig. 6).

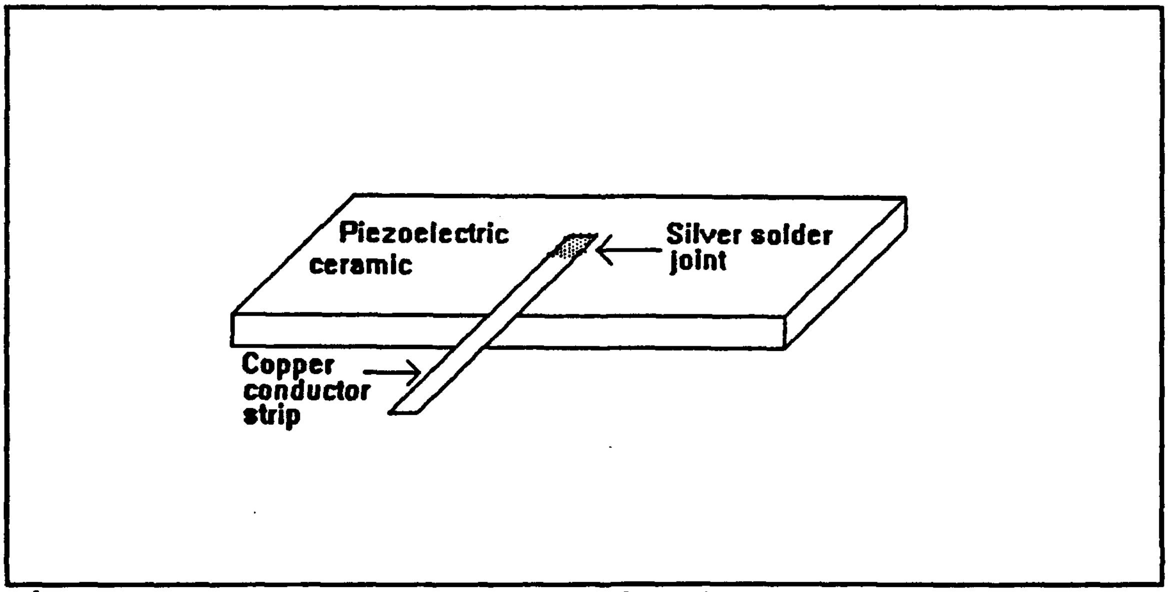

Figure 6 Copper conductor attachment

Place a small drop of liquid rosin flux in the center of the piezoelectric ceramic at the solder joint location. Lightly tin a clean hot soldering iron with silver solder. Using tweezers hold the copper conductor on the piezoelectric ceramic on the liquid flux. Touch the tinned soldering iron to the copper conductor and allow capillary action of the nickel plating and the conductor to draw the silver solder from the iron. Hold all edges flat and ensure the joint is of minimum thickness. Minimize the time the heat is applied with the soldering iron to prevent possible localized depoling of the piezoelectric ceramic. Once the joint has been cooled pull lightly to check the joint tightness. A resistance or capacitance meter can be used to check the electrical connection. Note: It may be necessary to lightly tin the copper conductor to obtain a good solder joint.

Using the same technique as above, solder an additional copper conductor on the opposite side of the piezoelectric ceramic. Offset this conductor from the other conductor so they will not contact and short out (Fig. 7).

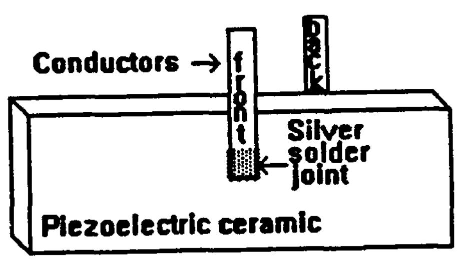

Figure 7 Conductor placement on piezoelectric ceramic

4. Insulating Conductors

Remove any slack from the conductor strip and place a small piece of Kapton® tape around the conductor such that the tape will butt up with the edge of the piezoelectric ceramic. This will prevent the copper conductor from bending or folding over the edge of the piezoelectric ceramic and short across the opposite side (Fig. 8).

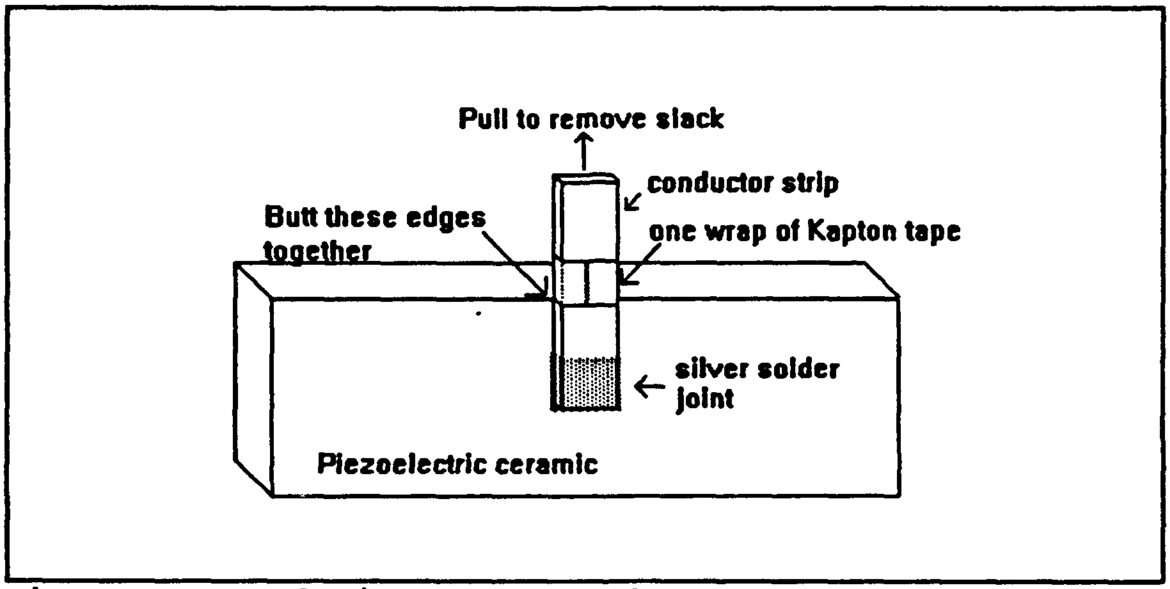

Figure 8 Insulating copper conductors

E. ATTACHING PIEZOELECTRIC CERAMICS TO A BEAM

1. Cleaning Piezoelectric Ceramics

Clean the piezoelectric ceramics with ethanol alcohol. A cotton ball or Q-tip® works well to apply the alcohol. Ensure all liquid flux is removed from the piezoelectric ceramic, solder joint, and copper conductor. Allow surface to air dry. Do not touch clean piezoelectric ceramics with bare fingers.

2. Gluing to Beam

Apply a uniform thin layer of super glue gel over the entire surface of the piezoelectric ceramic on the face to be adhered to the beam. Carefully place the glue side of the piezoelectric ceramic to the beam in the desired position. Keep in mind poling direction, conductor orientation, and allowable clearances for clamping devices. Hold the piezoelectric ceramic in place until the glue sets up. Ensure there are no air gaps between the piezoelectric ceramic and the beam. CAUTION: Super glue gel bonds readily to the skin. Remove excess super glue that oozes from under the piezoelectric ceramic with a Q-tip®.

3. Making a Stacked Actuator

Using technique D.3, solder a copper conductor strip in the center of the piezoelectric ceramic on the side that will not come in contact with the piezoelectric ceramic beneath it. Insulate conductor as in D.4.

Apply one spot of silver paste on the conductor of the already attached piezoelectric ceramic. Cover the rest of the piezoelectric ceramic surface with super glue gel and attach the top piezoelectric ceramic using technique E.2 (Fig. 9).

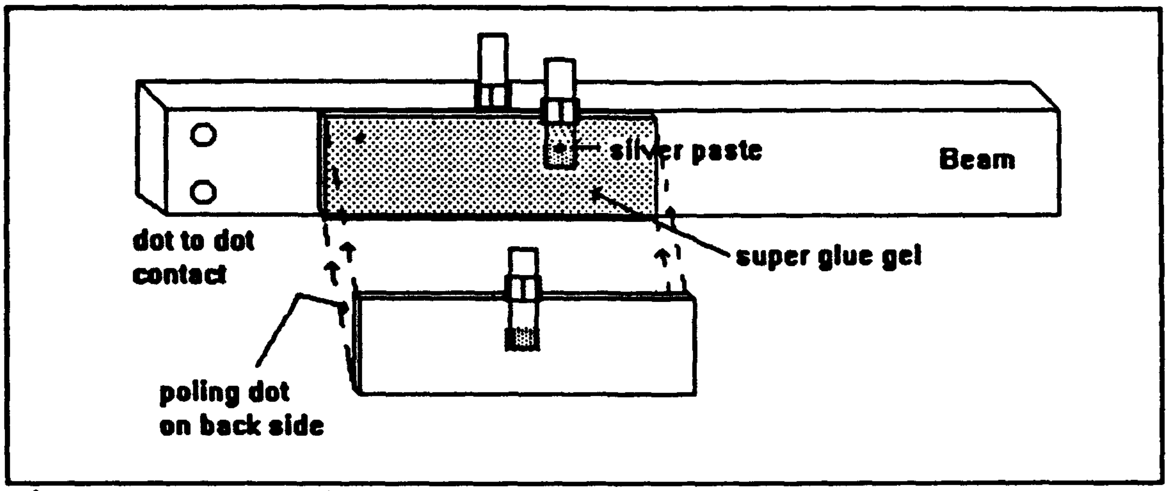

Figure 9 Stacked actuator

F. WIRING ARRANGEMENT

1. Soldering Conductors and Wires

Using flux and silver solder, solder all copper conductors of the same polarity (+/-, or -/+) together. Thin, (22 gage), insulated wire can be soldered to these junctions to allow powering the actuators and sensing the strain (Fig. 10).

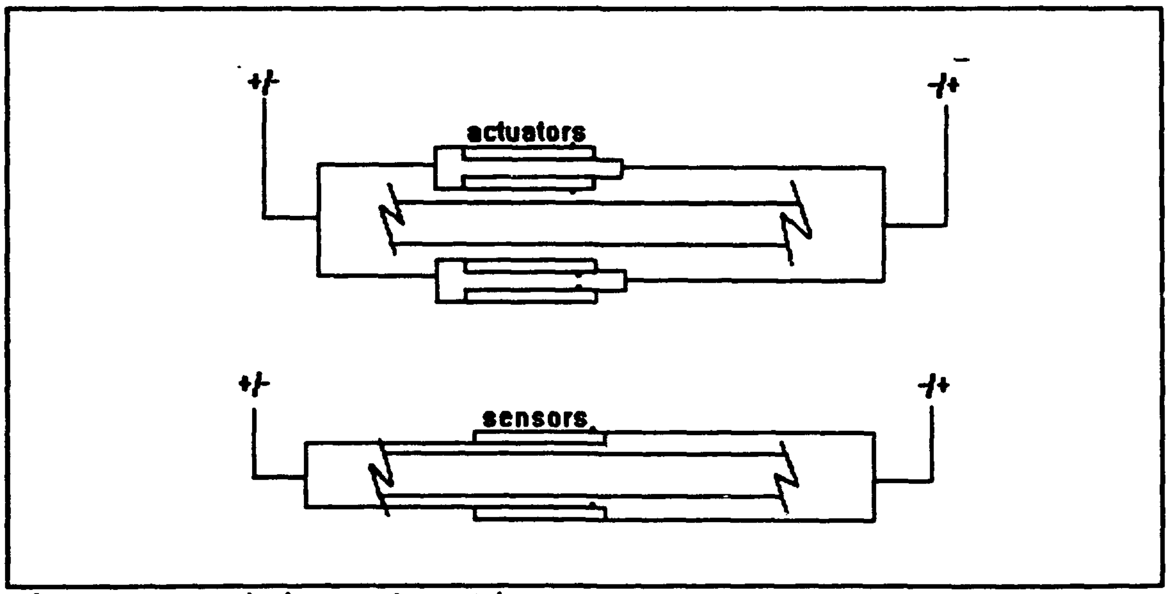

Figure 10 Wiring schematic

2. Poling arrangement for FSS

The FSS at the Naval Postgraduate School has three sets of piezoelectric ceramic sensors and actuators labeled A, B, and C. The actuators are in a stacked configuration with two piezoelectric ceramics on each side of the beam. The poling arrangement for the piezoelectric ceramic actuators and sensors for the FSS is illustrated in Fig. 11.

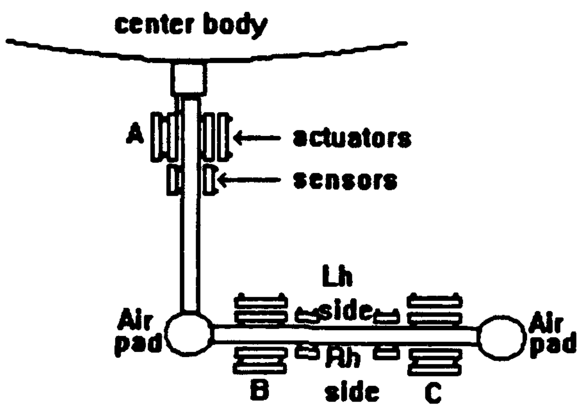

Figure 11 FSS piezoelectric ceramic poling arrangement

III. EXPERIMENTAL ANALYSIS

A. Physical Setup

The Flexible Spacecraft Simulator employs a center body, supported by air pads on a large granite table, which is free to rotate on an air bearing. An L-type flexible arm is attached to the base, which represents flexible space structures. The center body has a momentum wheel, air thruster, and rate and position sensors (Fig. 12). There have been various researches on the slew maneuver of this model using different control laws [Ref. 4].

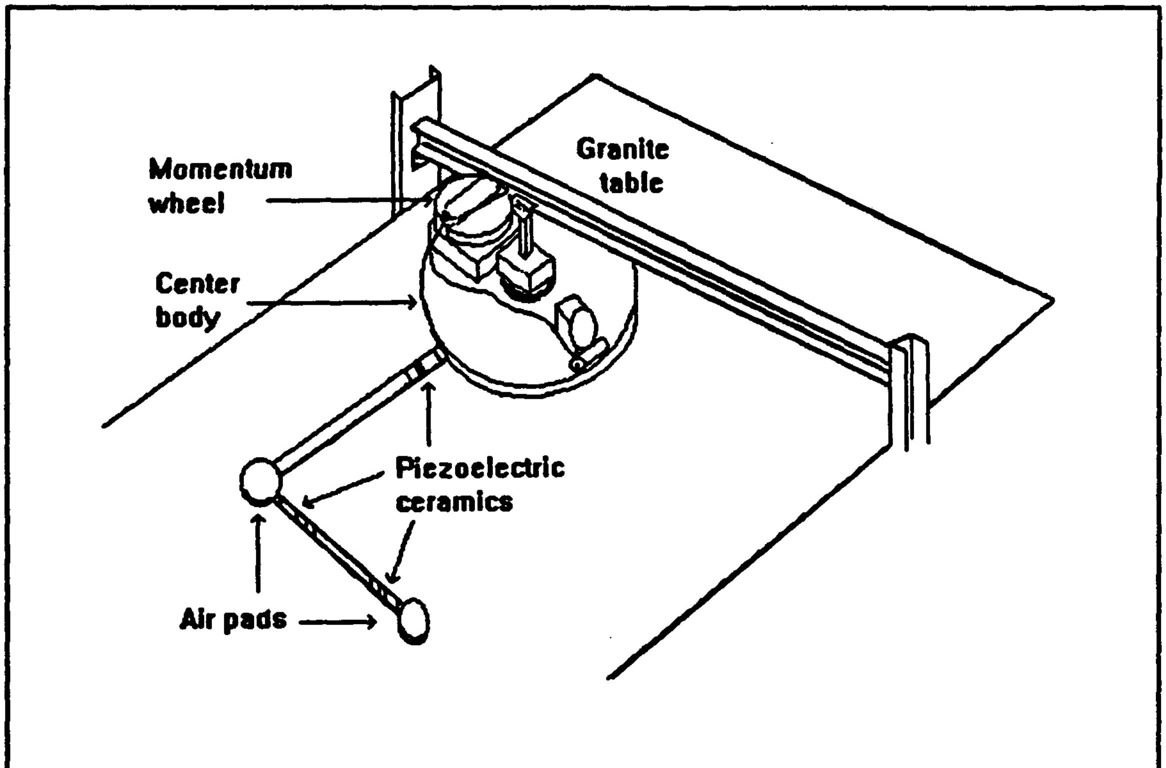

Figure 12 Flexible Spacecraft Simulator

In this study, the base is fixed, so that the flexible arm is free of rigid body mode coupling. The coupling between piezoelectric ceramic sensors/actuators and the center body rotation, is left to be investigated in the future.

Attached to the center body is a flexible arm which has two segments joined by an air pad to make a 90 degree elbow. Three sets of piezoelectric ceramic actuators and sensors are mounted on the flexible arms: one at the base of each arm and one at the tip of the second arm.

All three sets of actuators and sensors are wired using the same sign convention. The polarity is determined by placing the right hand side of the beam in compression while the left hand side is in tension. All wires are routed to minimize torquing or pre-loading of the beam. The wires are labeled as follows:

Number	Description	Color
A1	+ sensor A	yellow
A2	- sensor A	orange
A3	+ actuator A	purple
A4	- actuator A	blue
B1	+ sensor B	white
B2	- sensor B	green
B3	+ actuator B	red
B4	- actuator B	black
C1	+ sensor C	white
C2	- sensor C	green
C3	+ actuator C	red
C4	- actuator C	black

Note: The polarities indicated are determined by bending of the beam. When power is sent to the actuators for active damping, the polarity sent to the actuators will be opposite

of what the actuator has generated due to the strain in the beam. Wires numbered two and three are grounded to the beam, while those numbered one and four are the signal wires to the sensors and actuators respectively.

B. Control Law

A significant amount of attention has been focused on the analysis and control system design for piezoelectric ceramics. Both analytical and experimental approaches have been tested which are supported by successful results.

One of the main characteristics of the piezoelectric ceramic sensor is the measured variable, voltage, corresponding to total strain on the structure. This inherent nature of the piezoelectric ceramic has motivated the so-called Positive Position Feedback (PPF), which has appeared frequently in recent studies.[Refs. 1,5] The essential nature of PPF lies in the use of position information which is, in turn, used to build control laws in a position feedback form. The PPF has a close connection to the direct velocity feedback in the sense that the closed loop damping is the only design parameter to be changed. It turns out that the PPF can achieve stability of the system when actuator dynamics are included.

In addition to the PPF, other control laws such as Linear-Quadratic-Gaussian (LQG), and direct velocity feedback have been tested [Ref. 6]. The high sensitivity of sensor output,

usually, produces a reliable signal which is used to design successful stabilizing control laws.

Once again, the nearly co-located sensor/actuator system makes it possible to build a stabilizing set of PD control laws. In this study, PPF control law is mainly used to test the newly implemented sensor/actuator systems. In addition, Proportional-Derivative (PD) control laws are implemented as part of digital control loop. Even if the PPF has been named differently, the essential idea of PPF is based upon the direct velocity feedback. This can be easily explained by the compensator output (for the PPF) which is simply shaped velocity information.

Further effort has been made in this study in attempting to implement PD control law, for which the result can be compared with the PPF case. Most of the preliminary work on the PD control law has been completed by implementing the control laws into a software-based graphical control system design tool, which is called LABVIEW 2®.

Each set of sensor/actuator system can be used as an independent decentralized control law which stabilizes the system irrespective of the existence of the other two sets.

The test results tell us that the sensor output is clean enough to be used directly for a derivative feedback as well as a position feedback; and the dynamics of the actuator is almost negligible concerning stability issues.

The Macintosh Computer and LABVIEW 2® software, developed by National Instruments, were used to implement control laws for the piezoelectric actuators and sensors. All inputs from the sensors pass through an Analog to Digital converter (A/D) in the data acquisition board, thereby permitting digital control laws to be developed. A Proportional-Derivative (PD) controller was chosen for ease of implementation and guaranteed stability. The stability guarantee is one of the most elegant properties of the co-located sensor/actuator system for flexible structure control law. It is well known that the PD control laws globally stabilize the system even in the existence of non-linearities related to structural modeling or unknown external disturbances. The software package will enable the control laws to be easily changed for future research. The graphical user interface capability of the software, allows the user to easily change corresponding feedback gains.

C. Testing

Two sets of Proportional-Integral-Derivative (PID) control laws were built using the LABVIEW 2® software on the Macintosh computer. These controllers were built with the intention of using it as a PD controller by zeroing the integration component by setting the integral control time to zero. The system block diagram (Fig. 13) illustrates the controller components and input output (I/O) channels.

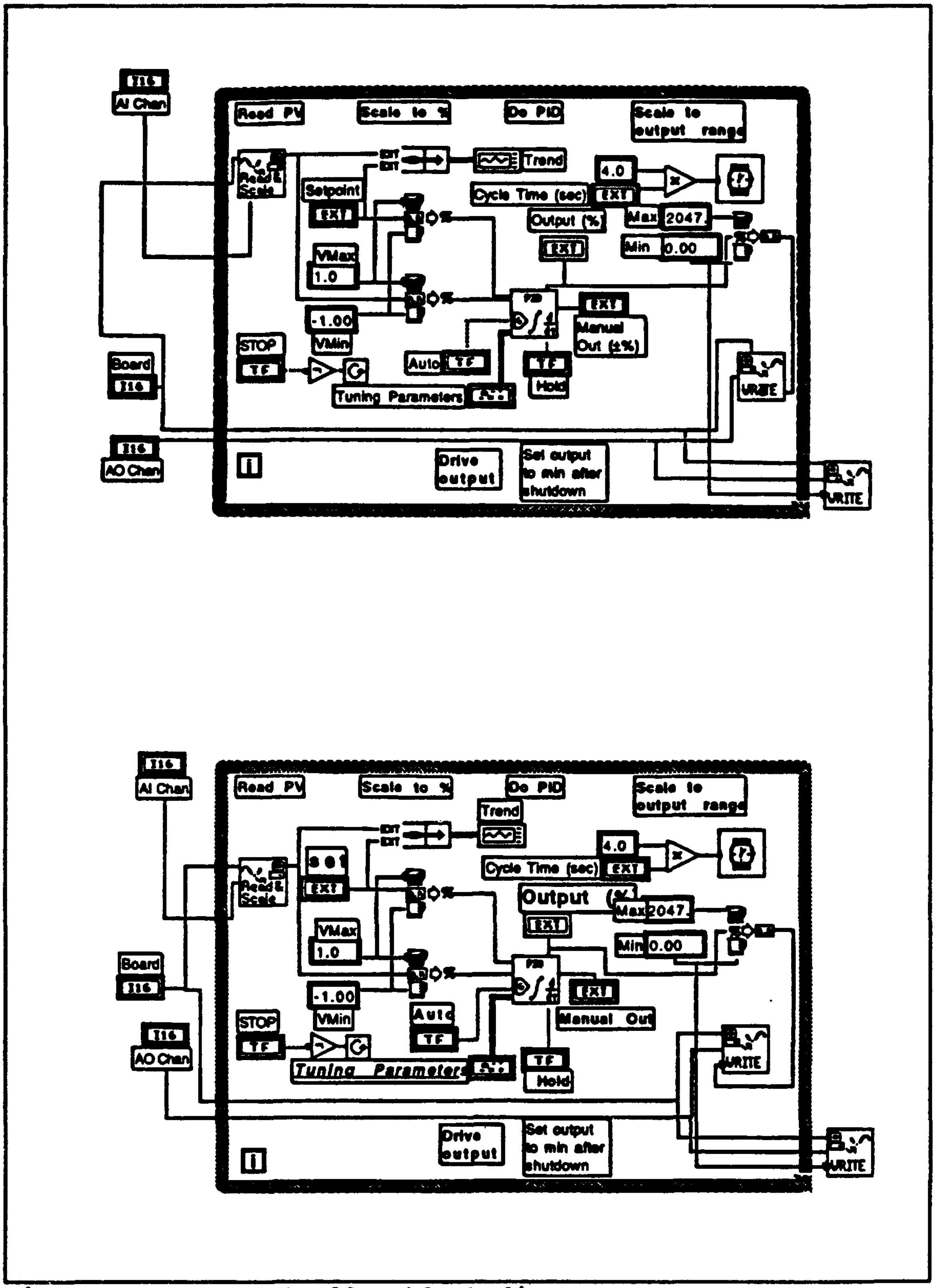

Figure 13 PID controller block diagram

An animated control panel (Fig. 14) allows the operator to vary all tuning parameters, and operate the controller via the mouse. This type of control setup, using a Virtual Instrument (VI), is very flexible and easy to use. A block diagram of the PID controller connected to the FSS illustrates the total system operation (Fig. 15).

Due to a circuit card failure in the Macintosh computer, the PID controller did not complete testing. In order to test the sensors and actuators lettered B and C on the FSS, the existing PPF controller was used to demonstrate active damping. The PPF controller, installed on the FSS, was designed to control fundamental vibrational modes using sensor A and actuator A. This controller can not be tuned to different frequencies or vibrational modes such that exist with the B and C sets, which usually measure high frequency components. The damping illustrated, using the PPF controller on B and C sensors and actuators, is not optimum, but does validate the system response.

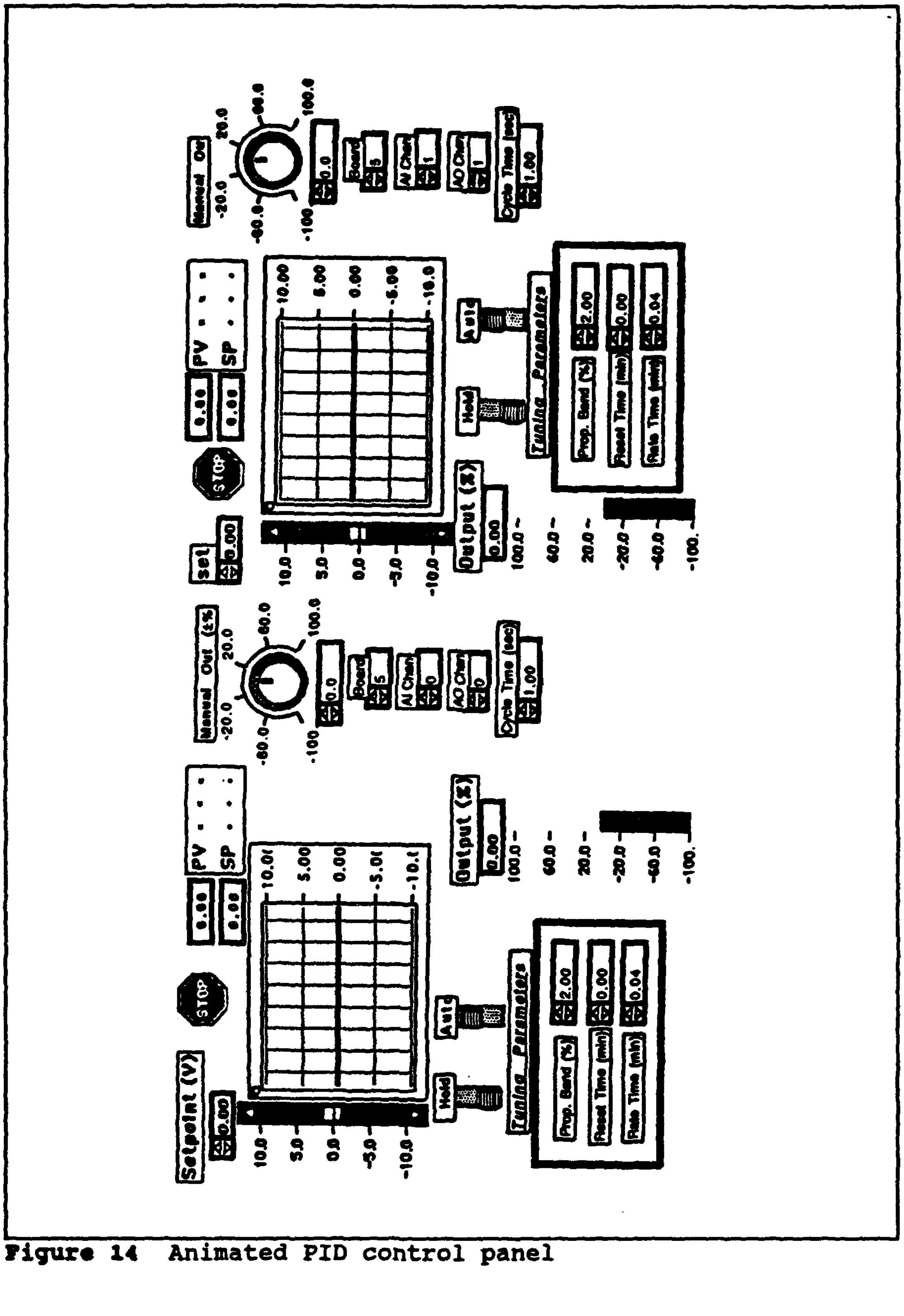

Figure 14 Animated PID control panel

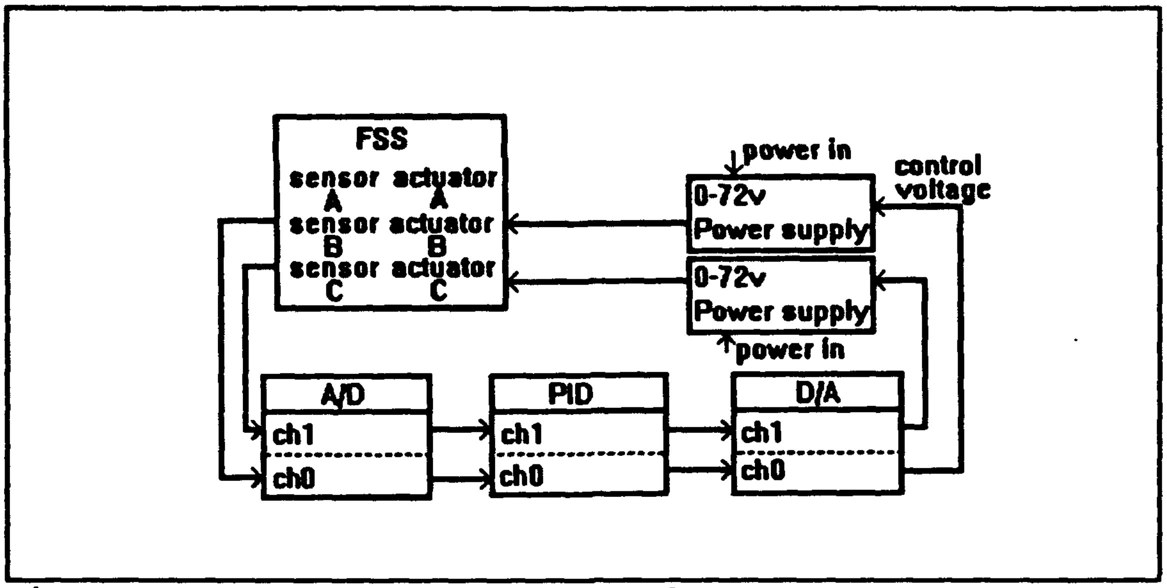

Figure 15 PID controller connected to FSS

D. Results

All actuators and sensors (sets A,B, and C) develop clean voltage signals when subjected to strain. Oscilloscope readings indicate voltage values from positive ten to negative ten volts. The relationship between voltage and strain for the sensors can be calculated as follows:

Sensor type - Navy Type II PZT

Dimensions - 1"x 1"x.01" (sensors)

- 2.5"x 1"x .01" (actuators)

Charge Q:

$$Q=AEd_{31}(\epsilon_1+\epsilon_2) \tag{1}$$

Sensor Capacitance C:

$$C=DA/t \tag{2}$$

Voltage Produced V:

$$V=Q/C=t(Ed_{31}/D)(\epsilon_1+\epsilon_2) \tag{3}$$

Where:

Q = charge in coulombs
A = area in m^2
d_{31} = lateral strain coefficient = $1.66x10^{-10}$ m/v or C/N
E = Young's Modulus = $6.9x10^{10}$ N/m^2 or Pa
ϵ = strain in $\mu m/m$
D = permitivity = $1.5x10^{-8}$ F/m

Calculations:

$$Q = (1x1)(6.9x10^{10})(1.66x10^{-10})(\epsilon_1+\epsilon_2)(2.54)^2(1/100)^2$$

$$= 7.39x10^{-9}(\mu\epsilon_1+\mu\epsilon_2)$$

$$C = (1.5x10^{-8})(2.54/.01)(1/100)$$

$$= .0381\ \mu F$$

$$V = (7.39x10^{-9})/(.0381x10^{-6})$$

$$= .194 \text{ Volts/microstrain}$$ [Ref.2]

The PID controller did not get to complete all testing due to a circuit card failure in the Macintosh computer. Two channels were being used to condition output from sensors B and C. The controller did successfully control the output voltage of the power supply in response to the vibrational disturbance placed on the flexible beam, however active damping was not demonstrated. This experiment, although not a complete success, did introduce digital control approaches for the FSS and also demonstrated the feasibility of using a software VI.

To demonstrate active damping of sets B and C, the PPF controller, hard mounted on the FSS, was used. Data acquisition was obtained using the AC-100, a real time controller developed by Integrated Systems, and $Matrix_x$® software, connected to read piezoelectric ceramic output voltage. A ten hertz data collection update rate was used to cover sufficient number of frequency components in the responses. The first three natural frequencies turned out to be less than one hertz which validates the update rate.

On the first trials, the beam was given a first mode disturbance. Strain measurements were taken from both the sensors and actuators for each set (Figs. 16-18). Data was also taken in a similar manner for the second mode of vibration of the beam (Figs. 19-21).

Active damping was demonstrated for all three sets of sensors and actuators for first mode vibrations using the PPF control box (Figs. 22-24).

Analysis shows that sensor/actuator pairs, co-located at the base of the beam, are much more efficient than those sensor/actuator pairs co-located at the tip of the beam. It is also worthwhile to note that the piezoelectric ceramic sensors and actuators have a bias to them which is due to residual strain from mounting, and also from charge dissipating through the common ground beam. This bias must be accounted for to achieve higher efficiencies in damping. One

possible solution that has worked well in past experiments, is to connect the sensors and actuators in a differential configuration. This will eliminate the bias component from the processed signal in the controller.

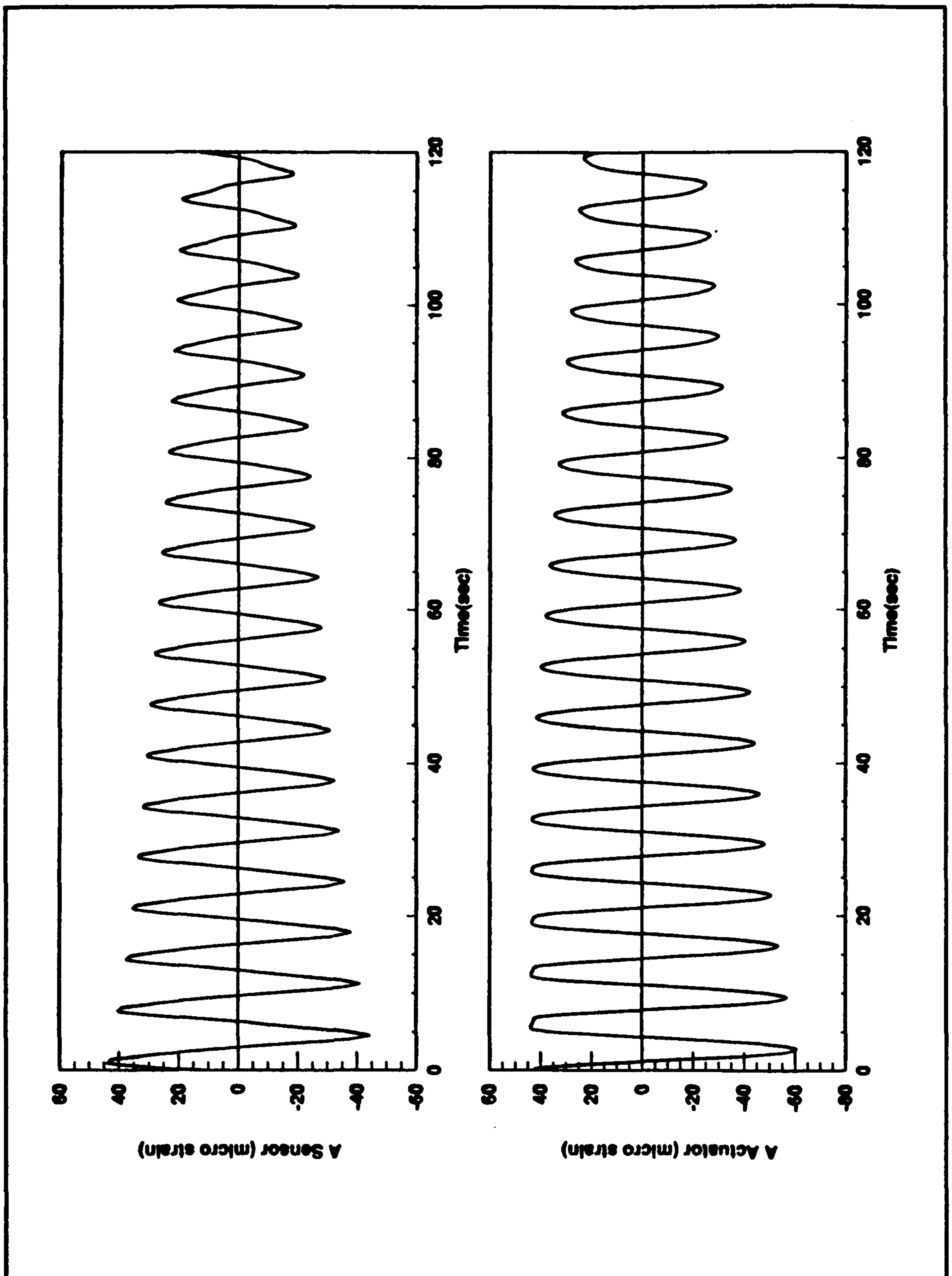

Figure 16 Set A sensor and actuator undamped first mode output

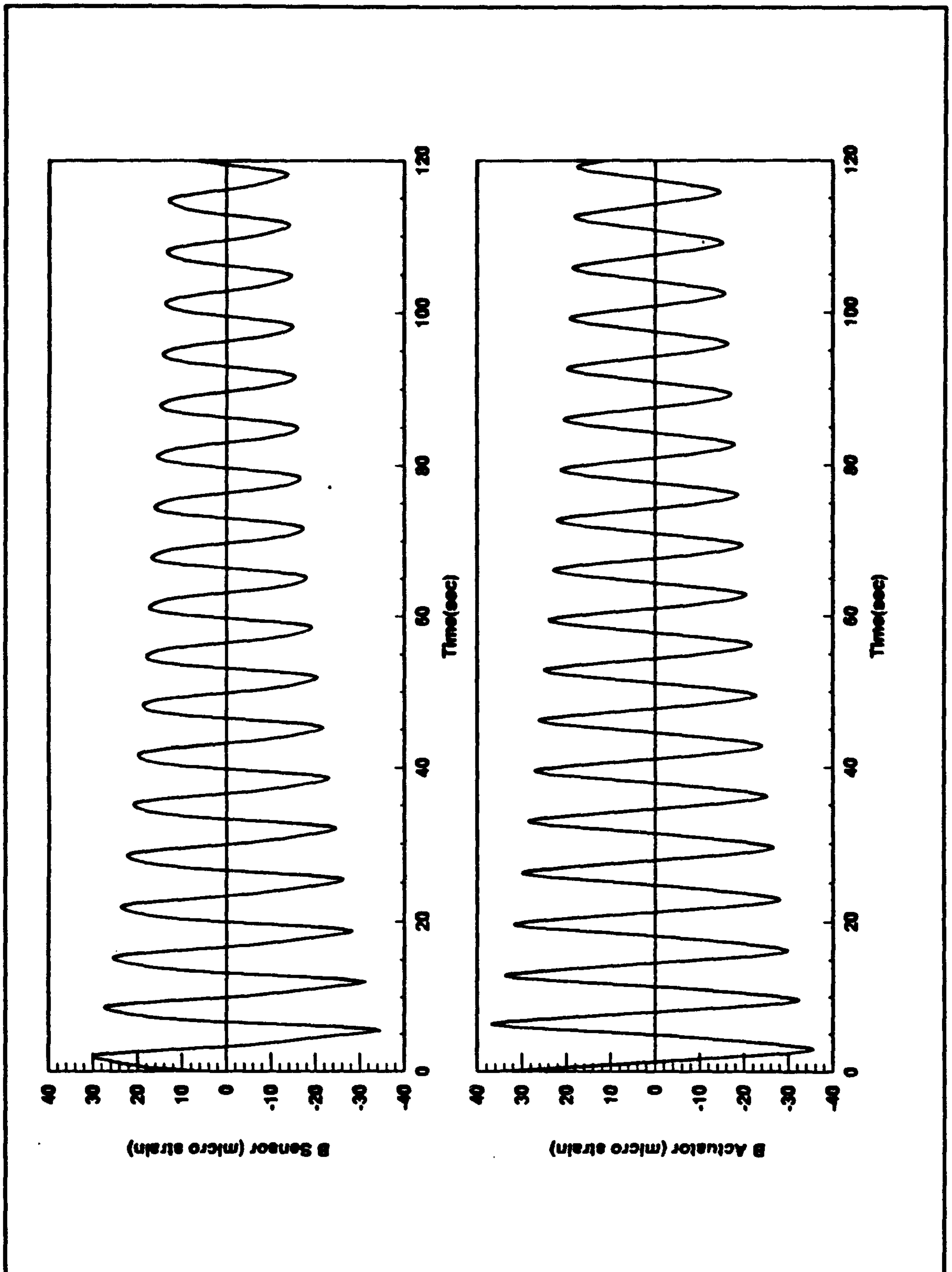

Figure 17 Set B sensor and actuator undamped first mode output

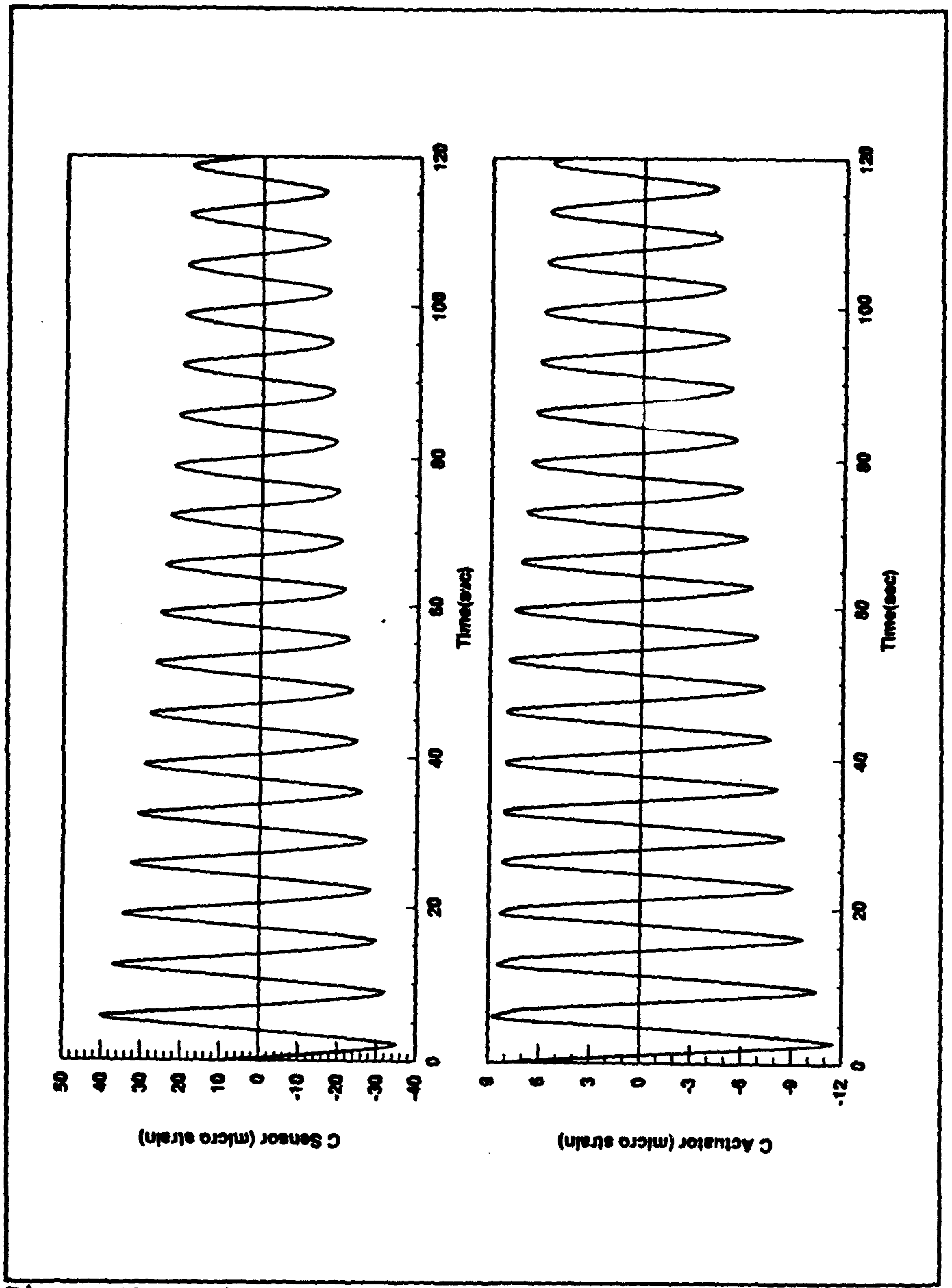

Figure 18 Set C sensor and actuator undamped first mode output

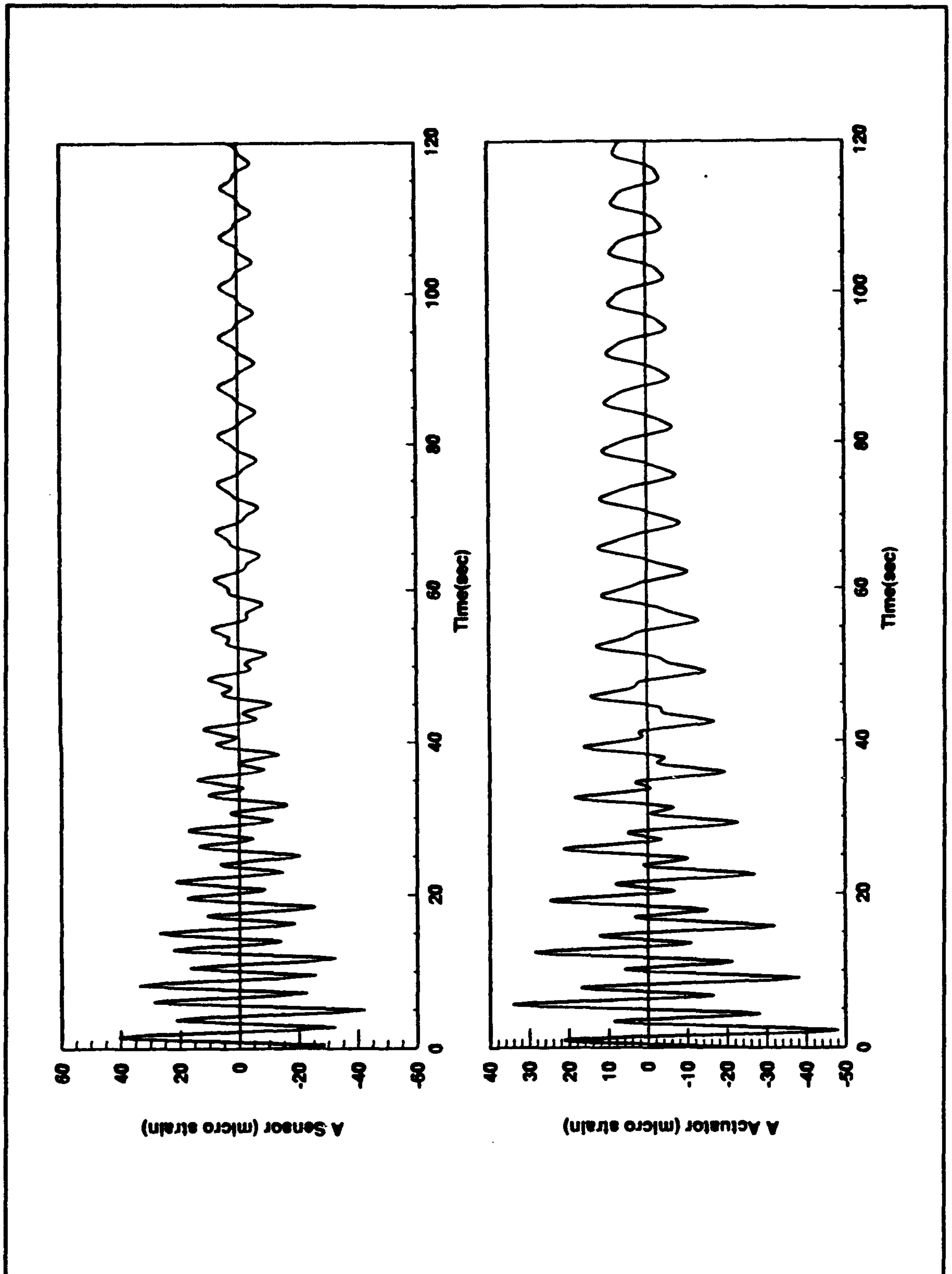

Figure 19 Set A sensor and actuator undamped second mode output

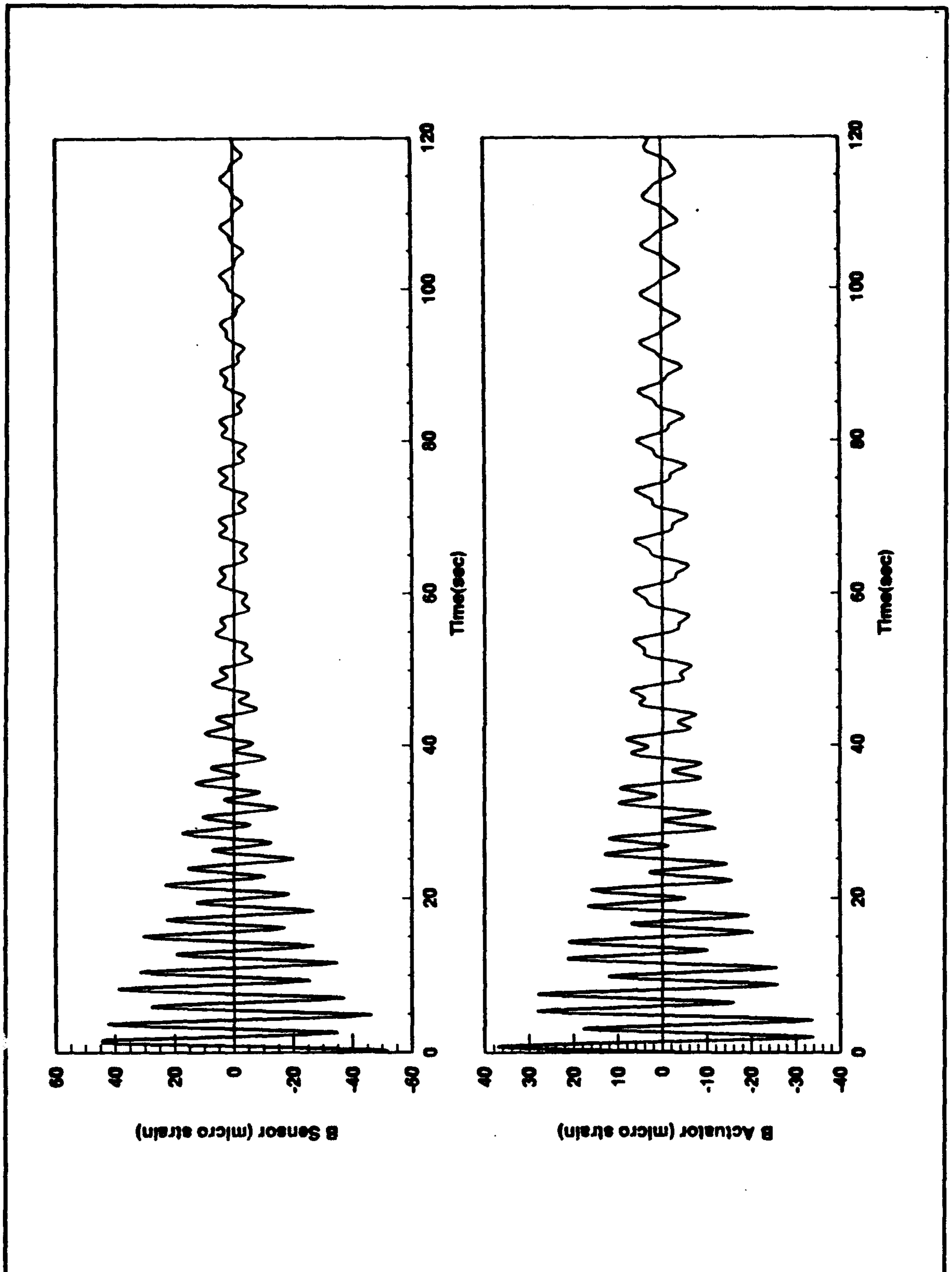

Figure 20 Set B sensor and actuator undamped second mode output

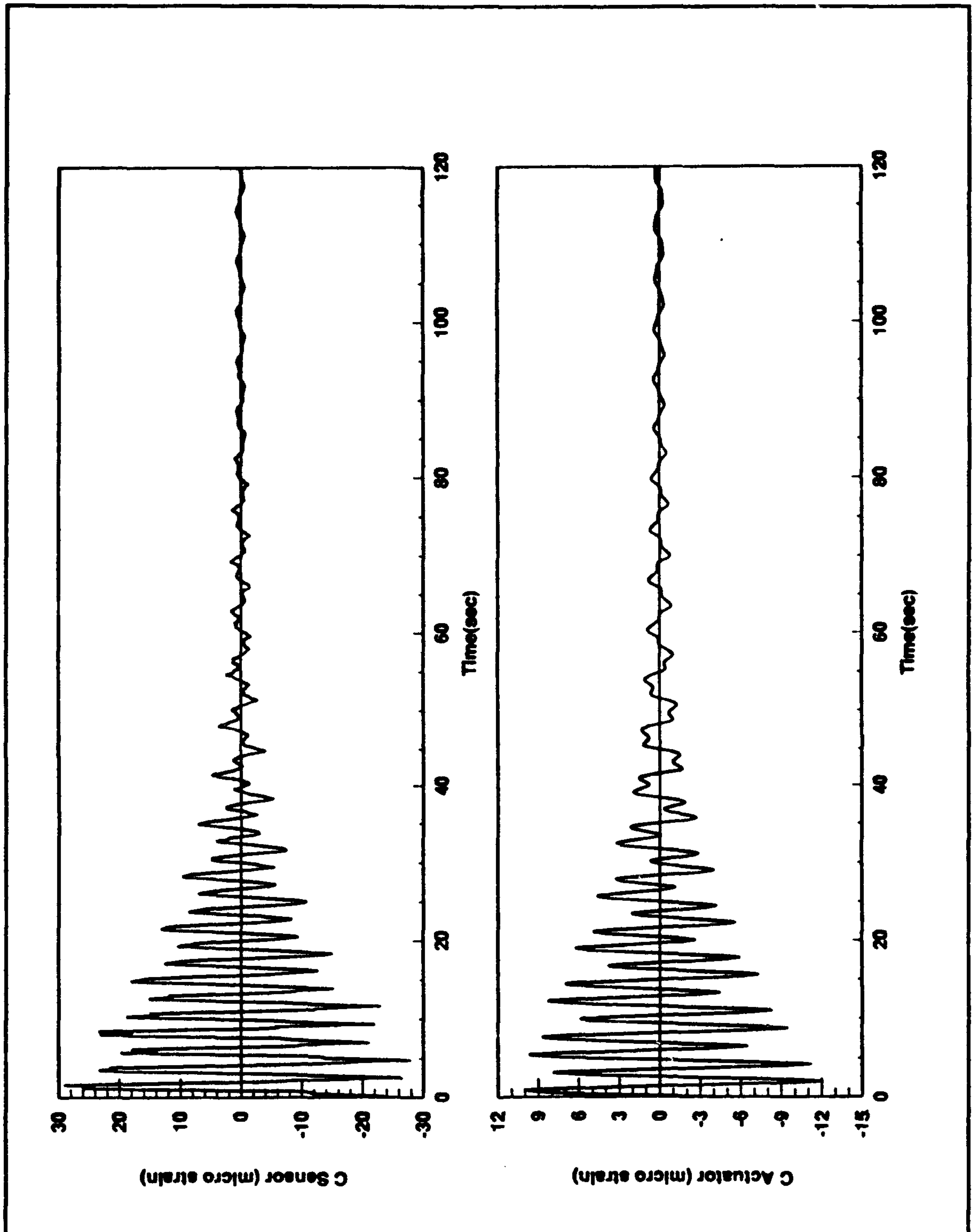

Figure 21 Set C sensor and actuator undamped second mode output

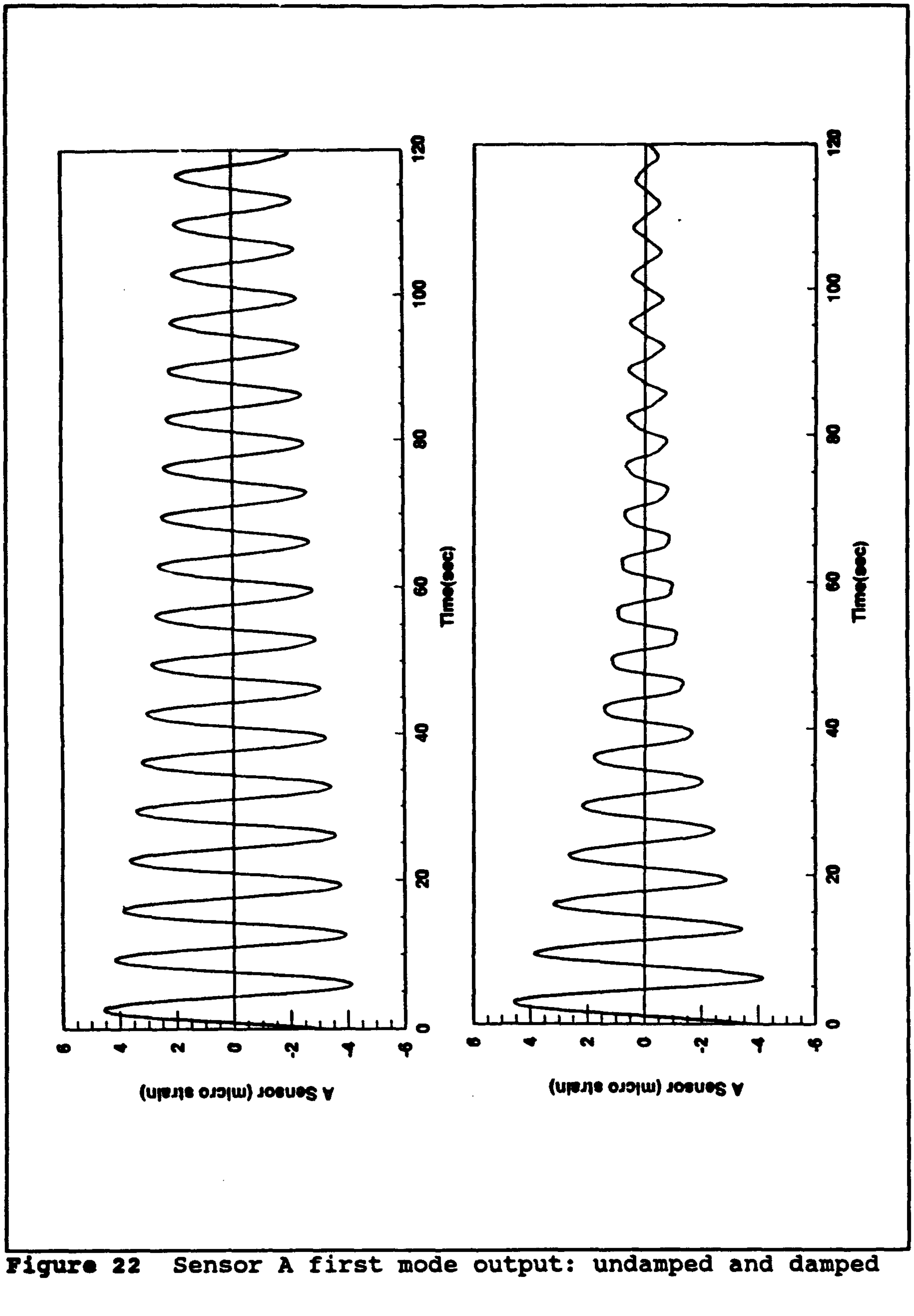

Figure 22 Sensor A first mode output: undamped and damped

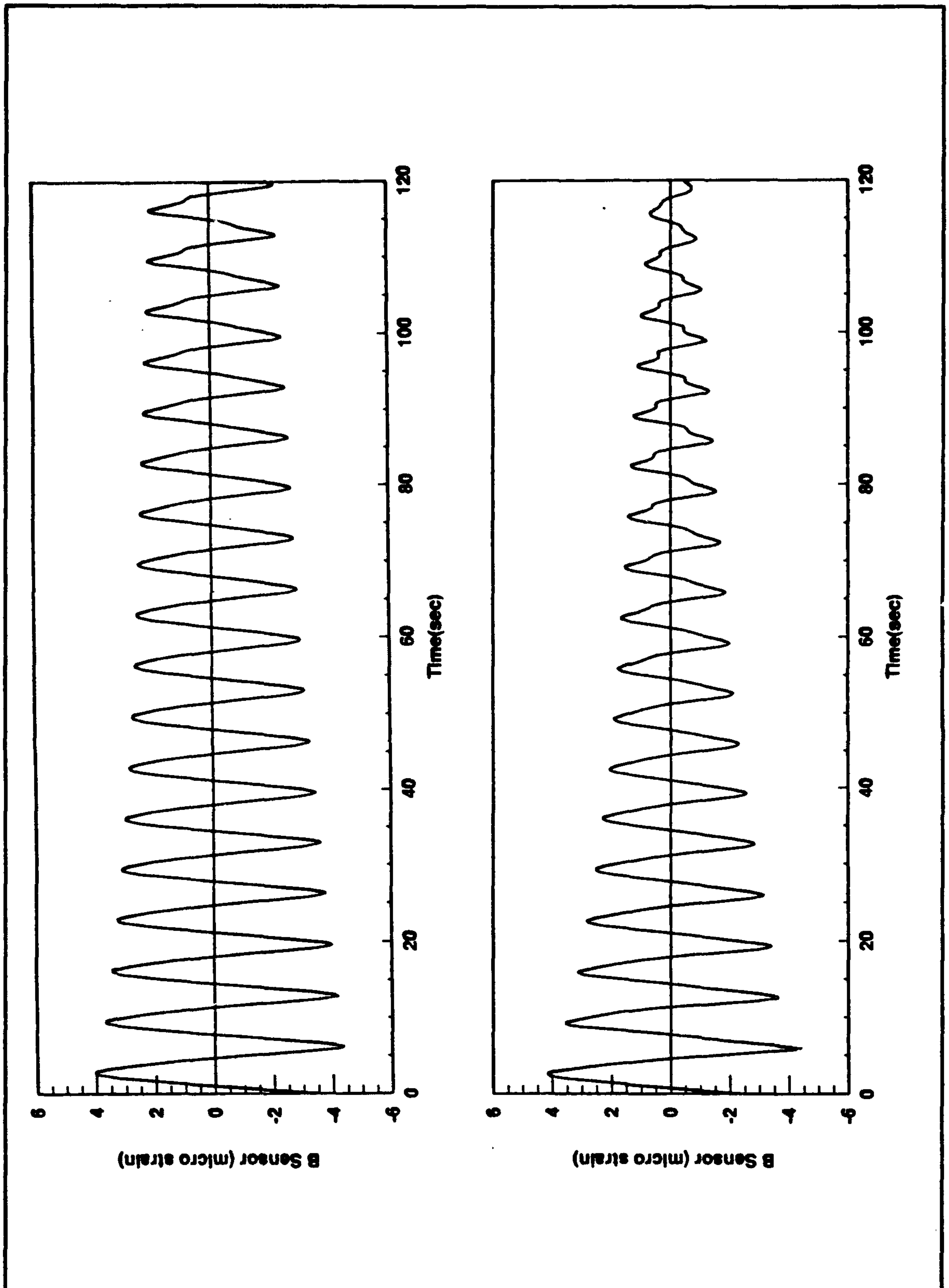

Figure 23 Sensor B first mode output: undamped and damped

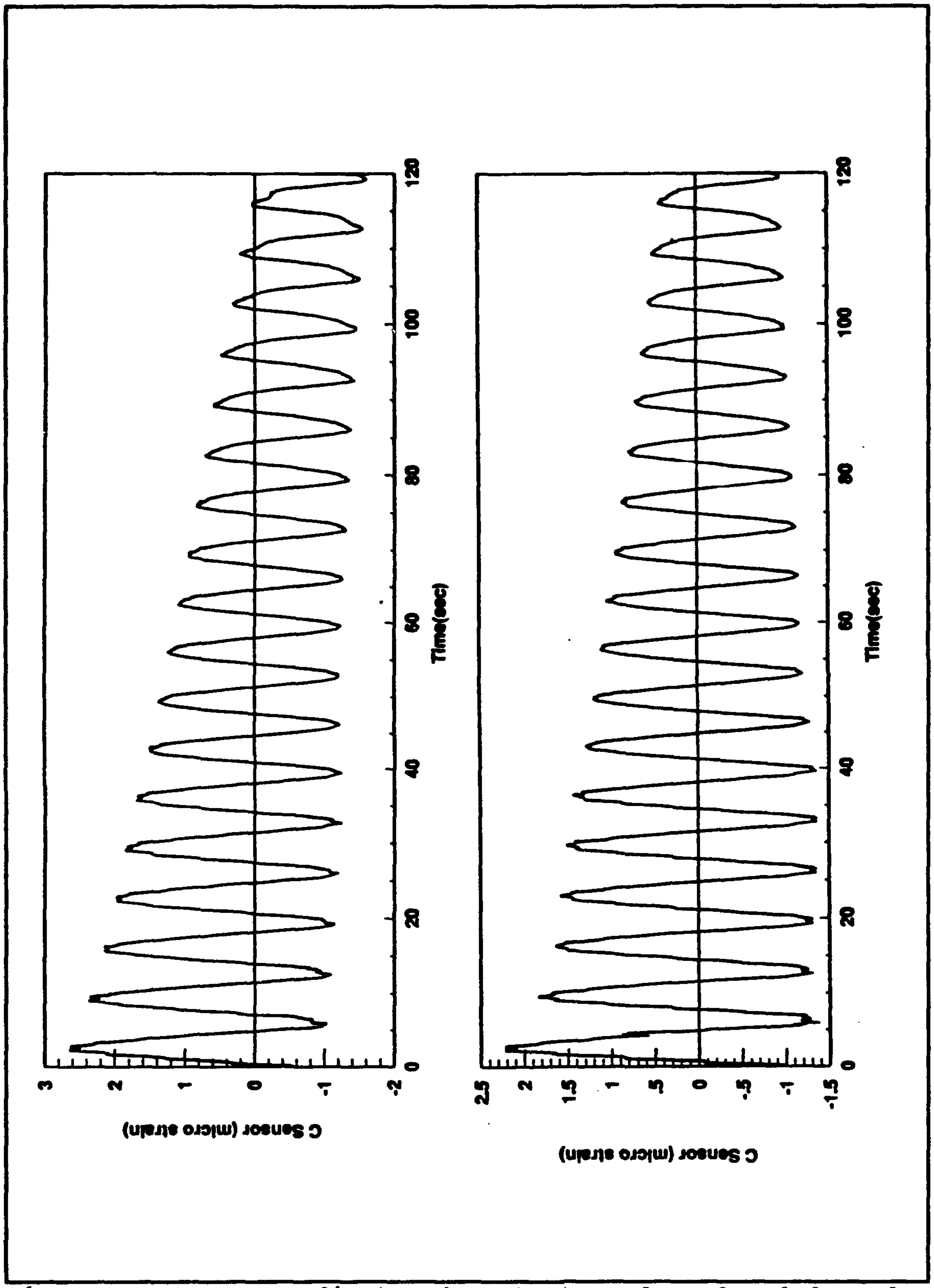

Figure 24 Sensor C first mode output: undamped and damped

IV. CONCLUSIONS

This thesis has greatly improved the versatility of the FSS in the following ways: Three sets of piezoelectric ceramic actuators and sensors are now operational for future research and demonstrations; a proven procedure has been established to properly mount and test piezoelectric ceramic material for the purpose of active damping; hardware and software to support digital controls have been successfully demonstrated; and a software virtual instrument controller has been implemented and is now available.

Recommendations for further study include: building a three channel virtual instrument, with a three channel power amplifier, for simultaneous, independent damping using all three sets of actuators and sensors on the FSS; an optimization study of various control laws for different FSS maneuvers; further enhancement, of the stabilizing control laws used in this thesis, in combination with optimal performance requirements

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